available at www.sciencedirect.com

ScienceDirect

journal homepage: www.elsevier.com/locate/agwat

# Corn yield responses under crop evapotranspiration-based irrigation management

*Jonghan Ko*[a,1,*], *Giovanni Piccinni*[b,1]

[a] *USDA-Agricultural Research Service, Agricultural Systems Research Unit, 2150 Centre Ave., Bldg. D, Suite 200, Fort Collins, CO80526, United States*

[b] *Monsanto Company, 700 Chesterfield Pkwy West, Chesterfield, MO 63017, United States*

ARTICLE INFO

*Article history:*
Received 25 July 2008
Accepted 29 October 2008
Published on line 10 December 2008

*Keywords:*
Corn
Crop evapotranspiration
Irrigation
Yield

ABSTRACT

Improving irrigation water management is becoming important to produce a profitable crop in South Texas as the water supplies shrink. This study was conducted to investigate grain yield responses of corn (*Zea mays*) under irrigation management based on crop evapotranspiration ($ET_C$) as well as a possibility to monitor plant water deficiencies using some of physiological and environmental factors. Three commercial corn cultivars were grown in a center-pivot-irrigated field with low energy precision application (LEPA) at Texas AgriLife Research Center in Uvalde, TX from 2002 to 2004. The field was treated with conventional and reduced tillage practices and irrigation regimes of 100%, 75%, and 50% $ET_C$. Grain yield was increased as irrigation increased. There were significant differences between 100% and 50% $ET_C$ in volumetric water content ($\theta$), leaf relative water content (RWC), and canopy temperature ($T_C$). It is considered that irrigation management of corn at 75% $ET_C$ is feasible with 10% reduction of grain yield and with increased water use efficiency (WUE). The greatest WUE (1.6 g m$^{-2}$ mm$^{-1}$) achieved at 456 mm of water input while grain yield plateaued at less than 600 mm. The result demonstrates that $ET_C$-based irrigation can be one of the efficient water delivery schemes. The results also demonstrate that grain yield reduction of corn is qualitatively describable using the variables of RWC and $T_C$. Therefore, it appears that water status can be monitored with measurement of the variables, promising future development of real-time irrigation scheduling.

Published by Elsevier B.V.

## 1. Introduction

Plant water is one of the most important and readily manageable variables for producing a profitable crop (Kozlowski, 1972; Taylor et al., 1983). Stresses that involve deficiencies of water will adversely affect cell turgidity, resulting in reduced crop production. A solution to water shortages has been irrigation, which has made agriculture possible in many nonproductive areas (Kramer and Boyer, 1995). In the Winder Garden area of Texas, irrigation is also one of the major limiting factors in producing corn and other crops.

Water for agricultural, urban and industrial use in the Austin–San Antonio–Uvalde corridor is pumped from the Edwards aquifer. This aquifer is in a class by itself being unique in terms of containment, recharge, and political

* *Corresponding author*. Tel.: +1 970 492 7370; fax: +1 970 492 7310.
E-mail address: Jonghan.Ko@ars.usda.gov (J. Ko).

[1] Previously, Texas A&M University, Texas AgriLife Research, 1619 Garner Field Road, Uvalde, TX 78801, United States.

*Abbreviations:* $ET_C$, crop evapotranspiration; $K_C$, crop coefficient; LEPA, low energy precision application; RWC, relative water content; $T_C$, canopy temperature; $\theta$, volumetric water content.

0378-3774/$ – see front matter. Published by Elsevier B.V.
doi:10.1016/j.agwat.2008.10.010

sensitivity. The regulation of this aquifer, however, is portent to the regulation of all aquifers in Texas. As the Texas Legislature placed water restrictions on the farming industry by limiting growers to a maximum use of 6100 $m^3$ $ha^{-1}$ of water per year in the Edwards aquifer region (Barrett, 1999), improving irrigation water management for crop production is becoming increasingly important in South Texas. The methods improving the efficiency of water use described by some researchers (Stewart and Nielsen, 1990; Taylor et al., 1983) are as follows: (1) increasing the efficiency of water delivery and the timing of water application, (2) increasing the efficiency of water use by the plants, and (3) increasing the drought tolerance of the plants. The first method depends on mostly engineering and has been successful in improving productivity per unit of water delivered to the farm. Irrigation application at critical growth stages is also important because it can conserve water and maintain yields. Musick and Dusek (1980) in the Texas Panhandle reported that stress during tasseling and silking was the most harmful and stress during grain filling was more harmful than stress during vegetative growth. The second and third methods depend on understanding physiological aspects and genetic characteristics of crops.

Corn grain yields are influenced by a number of environmental factors such as growing season weather conditions, water availability, and soil conditions. Soil moisture status is important in maintaining optimal corn yields, and maintaining optimal soil moisture is facilitated by irrigation. Summer annual crops such as corn expose yield reductions in response to soil water deficits at any growth phase (Denmead and Shaw, 1960; Howe and Rhoades, 1955; Musick and Dusek, 1980). However, if irrigation replenishes the profile moisture after the water stress is limited to one portion of the growing season, high yields can still be achieved (Stegman, 1982). To determine plant water status, measuring relative water content (RWC) of plant tissues has been widely accepted as a reproducible and meaningful index (Barrs, 1968; Smart and Bingham, 1974). The measuring technique was originally described by Weatherley (1950, 1951). Leaf tissues are most generally used for RWC determination. Meanwhile, crop canopy temperature ($T_C$) is an effective indicator of plant water stress because the temperature of most plant leaves are mediated strongly by soil water availability and its effect on crop evapotranspiration (Jackson, 1982; Jackson et al., 1981; Moran et al., 1997). Michels et al. (1999) described a way to monitor $T_C$ using infrared thermometers (IRT) mounted on center-pivot-irrigation system. Recently, Falkenberg et al. (2006) reported that $T_C$ observation using remote sensing could be useful to develop an efficient irrigation management system. In addition, using $T_C$ variability to initiate irrigation has the potential for significant water savings due to improved efficiency in the use of available soil water (Clawson and Blad, 1982).

It is important to understand water requirement and physiological aspects of crops under limited irrigation management in order to achieve optimal production. The purposes of this study were (1) to quantify corn yield responses under full and deficit irrigation managements based on evapotranspiration ($ET_C$), and (2) to evaluate some of physiological and environmental factors to monitor plant water deficit.

## 2. Materials and methods

### 2.1. Experimental field and irrigation

Corn was grown under a center pivot field irrigated with a least energy precision application (LEPA) system at the Texas AgriLife Research Center in Uvalde, Texas (29°13′03″N, 99°45′26″W; 283 m) in 2002, 2003, and 2004. Soil type was an Uvalde silty clay soil (fine-silty, mixed, hyperthermic Aridic Calciustolls with a pH of 8.1). Three commercial corn varieties used were 949 and 953 from Asgrow (St. Louis, MO) and 30G54 from Pioneer (Johnston, IA). These were planted on 6 March 2002, 18 March 2003, and 10 March 2004, and harvested on 9 August 2002, 20 August 2003, and 18 August 2004. The experimental site (~4.8 ha) was bedded in a circle that was planted at 64,220 seed $ha^{-1}$ on 1-m row spacings. Nitrogen was broadcast with a fertilizer spreader buggy at 112 kg $ha^{-1}$ for 3 years of the study. The field experiment was arranged in a split–split block design with each block replicated three times. A 90° wedge of the center pivot field was divided equally into 45° plots for conventional tillage and reduced tillage. Each split plot was subdivided into 7.5° regimes, which were maintained at 100%, 75%, and 50% crop $ET_C$ schemes.

Conventional tillage consisted of chisel plowing (20 cm), mouldboard plowing (20 cm), and shallow tillage (10 cm) and direct drilling while reduced tillage practiced only shallow tillage (10 cm) and direct drilling. As soon as plants reached complete stand in early April, furrow dikes were placed between beds and lanes were cut between irrigation regimes for the conventional tillage plot to increase water capture, minimize run-off, and maximize irrigation efficiency. Irrigation scheduling and ET regimes for the field were imposed according to daily calculations of the FAO Penman–Monteith equation (Allen et al., 1998). Actual crop water use requirements for corn were determined based on the relation to a well-watered reference grass. The equation was as follows:

$$ET_C = K_C \times ET_O \tag{1}$$

where $K_C$ is crop coefficient and $ET_O$ is reference evapotranspiration. ET from a tall fescue grass (*Festuca arundinacea* Schreb.) with a height of 0.12 m and a surface resistance of 70 s $m^{-1}$ became an $ET_O$ surface as the basis for $K_C$ and for modeling water use. Total amounts of irrigation for each year from plant to maturity were presented with weather conditions in Table 1. Rainfall was greatest in 2002 followed by 2004 and maximum air temperature was highest in 2003 followed

**Table 1 – Total irrigation applied and weather conditions during the crop growing season in 2002, 2003, and 2004 in the experimental fields at Uvalde, TX.**

| Year | Irrigation applied (mm) | | | Rainfall (mm) | Temperature (°C) | |
|---|---|---|---|---|---|---|
| | 100% $ET_C$ | 75% $ET_C$ | 50% $ET_C$ | | Max | Min |
| 2002 | 422.4 | 316.8 | 211.2 | 450.3 | 30.7 | 18.8 |
| 2003 | 417.8 | 313.3 | 208.9 | 276.6 | 31.2 | 18.2 |
| 2004 | 231.1 | 173.3 | 115.6 | 340.1 | 27.9 | 17.6 |

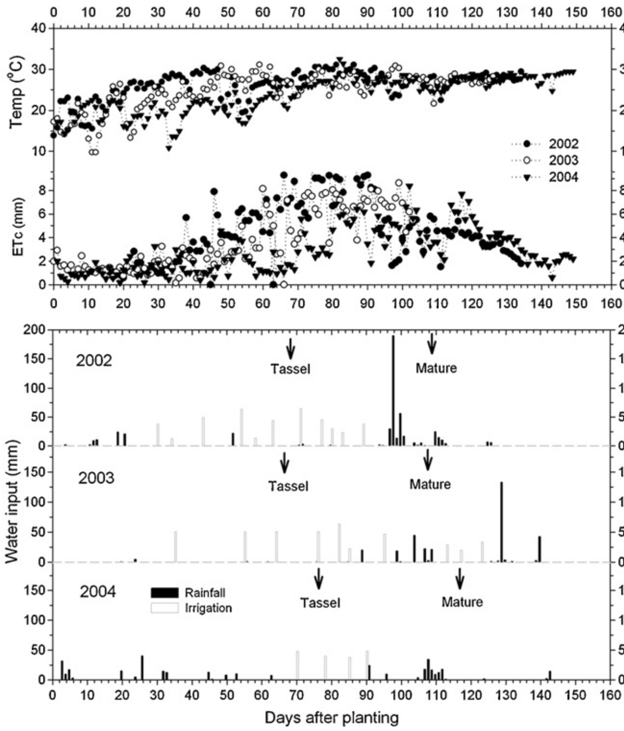


**Fig. 1 – Daily average air temperature and crop evapotranspiration ($ET_C$) (top), and water input (rainfall and irrigation) (bottom) during the growing seasons in 2002, 2003, and 2004 in Uvalde, TX.**

by 2002. Meanwhile, daily variations of air temperature and $ET_C$ were comparatively greater in 2002 and 2003, and there were more frequent rainfalls in 2004 (Fig. 1).

### 2.2. *Data measurement and analysis*

A neutron probe (530 DR Hydroprobe Probe Moisture Depth Gauge, Campbell Pacific Nuclear Corp. Int. Inc., Martinez, CA) was used to quantify soil moistures at various depths during the crop growing season in 2004. Measurement was made on day of year (DOY) 118, 126, 131, 138, 144, 153, 162, 168, 174, 196, and 203. After planting, neutron probe access tubes were installed at the center of each planting treatment plot. Volumetric water content ($\theta$) was determined using a linear equation as follows:

$$\text{water content (vol.)} = a \times \text{CR} + b \quad (2)$$

**Table 2 – Linear relationships between soil moisture and neutron probe (NP) ratio, *x*, at each depth (*n* = 12). The *x* is a target NP count divided by a standard NP count.**

| Soil depth (cm) | Linear equation | $R^2$ |
|---|---|---|
| 20 | 48.2*x* − 43.9 | 0.94 |
| 40 | 28.2*x* − 19.9 | 0.99 |
| 60 | 24.6*x* − 14.2 | 1.00 |
| 80 | 19.6*x* − 6.8 | 0.99 |
| 100 | 23.1*x* − 10.8 | 0.98 |

where *a* and *b* are coefficients, and CR is the count ratio (count divided by standard count). The coefficients were determined for each soil depth by experimentation measuring the soil moisture at different water contents with the neutron probe and measuring it also by taking a soil sample (Table 2). The soil samples were weighed and dried at 104 °C for 24 h and again weighed to calculate the dry weight moisture contents. The $\theta$ values determined by the neutron probe were also determined from the dry weight contents of the soil times the apparent specific gravity of the soils or bulk densities. The bulk densities were determined by measuring the volume of dry soil and the dry weight of that volume.

Three plants were randomly sampled from each plot to determine RWC of leaves on DOY 134, 144, 157, 163, 169 and 177 in 2002. The RWC determination was accomplished by excising 1-cm disks at the location of the uppermost collared leaf for each plant. The five disks from each pot were weighed immediately, providing a measure of fresh mass ($W_f$). After weighing, the disks were soaked in de-ionized water for 24 h and then weighed again to obtain a fully turgid mass ($W_t$). Finally, the leaf disks were dried at 85 °C and weighed to get a dry mass ($W_d$). The leaf RWC is calculated as follows (Salisbury and Ross, 1992):

$$\text{RWC} = \frac{W_f - W_d}{W_t - W_d} \quad (3)$$

To measure canopy temperature, IRT sensors (30 IRt/c.™ 01-T80F/27C, Exergen, Watertowon, MA) and a TVS-700 long wave-length infrared (LWIR) camera (Indigo System, Dallas, Texas) with an infrared band of 8–14 μm were used. The IRT sensors were mounted at ~4.5 m spacing along the pivot length to record canopy temperatures and measured the infrared band of 8–14 μm. The pixel size for the IRTs was 3.65 $m^2$ and has ~25 plants within each pixel. A CR23X (Campbell Scientific Inc., Logan, UT) recorded canopy temperature from the IRTs every 10 s, and averaged temperature values every 60 s. IRT corn canopy temperature readings were scheduled to measure at solar noon on sunny days. These were made on DOY 157, 161, 164, 171, and 176 in 2002. The TVS-700 LWIR camera was mounted in a helicopter to evaluate its ability to detect canopy temperature differences. The camera had a 35 mm lens able to measure temperatures from −20 to 500 °C. Images were taken at heights of 458–915 m and the pixel size of the images was ~0.61 $m^2$, which included 3–4 plants per pixel. The camera was used every 2–3 weeks depending on weather and availability from the company. In this manuscript, the imageries on DOY 141 and 145 in 2002 were presented.

Grain yields were determined by randomly sampling 3 $m^2$ for each plot. In this study, water use efficiency (WUE) was calculated using the following equation:

$$\text{WUE}_{I+R} = \frac{Y}{I + R} \quad (4)$$

where $\text{WUE}_{I+R}$ (g $m^{-2}$ $mm^{-1}$) is water use efficiency calculated with seasonal water input (mm), or irrigation (*I*) + rainfall (*R*).

The data were analyzed by analyses of variance using PROC GLM, standard errors of the mean using PROC MEANS, simple

**Table 3 – Corn grain yields under different tillage practices and irrigation regimes in 2002, 2003, and 2004 at Uvalde, TX.**

| Tillage | Irrigation | Grain yield (kg ha$^{-1}$) | | |
|---|---|---|---|---|
| | | 2002 | 2003 | 2004 |
| CT | 50% $ET_C$ | 6375.2 | 7025.0 | 6929.5 |
| | 75% $ET_C$ | 7109.8 | 7434.3 | 7492.0 |
| | 100% $ET_C$ | 7755.1 | 7878.9 | 7985.4 |
| RT | 50% $ET_C$ | 6093.6 | 5477.3 | 7745.8 |
| | 75% $ET_C$ | 7781.2 | 6477.9 | 7610.3 |
| | 100% $ET_C$ | 8442.4 | 7268.0 | 8567.0 |
| Means within tillage | CT | 7080.0 a | 7479.4 a | 7469.0 a |
| | RT | 7437.0 a | 6407.7 b | 7974.3 a |
| Means within irrigation | 50% $ET_C$ | 6234.3 b | 6251.2 c | 7337.6 b |
| | 75% $ET_C$ | 7445.5 a | 7006.1 b | 7551.1 b |
| | 100% $ET_C$ | 8015.5 a | 7573.4 a | 8276.2 a |
| ANOVA | | $P > F$ | | |
| | | 2002 | 2003 | 2004 |
| Tillage ($T$) | | ns | *** | ns |
| Irrigation ($I$) | | ** | *** | ** |
| $T \times I$ | | ns | ns | ns |

CT, conventional tillage; RT, reduced tillage; $ET_C$, crop evapotranspiration; ns, not significant. Means followed by the same letter within each column are not significantly different (LSD test at the 0.05 probability level).
** Significance at the 0.01 probability level.
*** Significance at the 0.001 probability level.

linear regression using PROC REG (SAS version 9.1, Cary, NC). All treatment means were compared using the LSD test at the 0.05 probability level.

## 3. Results and discussion

Corn grain yields varied between conventional tillage (CT) and reduced tillage (RT) practices for the 3 years (Table 3). The grain yields were not significantly different between the tillage practices in 2002 and 2004 while that was greater at CT in 2003. Under the different irrigation regimes, the grain yields were greater at 100% crop $ET_C$ and less at 50% $ET_C$ for the 3 years. Averaging the 3 year data, it appears that irrigation management of corn at 75% $ET_C$ is feasible with 10% reduction of grain yield. There were no significant differences among the varieties used in this study (data not presented). In addition, no interactions were found between the tillage and irrigation treatments for the 3 years. In the U.S. Corn Belt where conservation tillage studies were conducted, grain yields were maintained or increased (Lindstrom and Forcella, 1990; Mock and Erbach, 1997). In South Texas, Smart and Bradford (1999) reported that the grain yields for RT were less than those for CT in the first cropping year and were equivalent to the CT yields in the second and third years. However, the yields in this study varied for the 3 years. This type of yield response over the years may be due to crop rotations in our experiment field, in which the crop residues favorably or adversely affect the following crops. However, it is considered that the result generally agreed to the previous reports.

The present results also show that corn yield was reduced under the deficit irrigation levels. This corresponds to some of the results under different irrigation regimes in other regions. In Nebraska, Hergert et al. (1993) reported that corn was produced 5.6, 10.1, and 11.8 ton ha$^{-1}$ with dryland, limited irrigation, and full irrigation, respectively. In the Texas High Plains, there were some studies that reported yield depletion due to limited water application (Howell et al., 1990, 1995, 1998; Musick and Dusek, 1980; Tolk et al., 1998). Musick and Dusek (1980) advised that corn should be typically produced under moderately high irrigation levels due to the sensitivity of corn to water deficits. The following paragraphs discuss some factors that might influence the crop production under the tillage practices and irrigation regimes. The factors include volumetric soil water content ($\theta$), RWC of plants, and $T_C$.

Values of $\theta$ varied more in the upper soil layers over the growing season in 2004 (Fig. 2). The $\theta$ values were not significantly different between the two tillage practices in any soil layer during the season. On the other hand, the $\theta$ values were significantly different between 100% and 50% $ET_C$ after DOY 144 until 196 in all soil layers. However, 75% $ET_C$ was not significantly different from 100% $ET_C$, while 100% $ET_C$ was significantly different from 50% $ET_C$ most times between DOY 144 and 196. While there were no statistical differences between the tillage practices, the $\theta$ values at RT were numerically greater than those at CT in the upper soil layers in the mid and late growing season. The experimental plots were not maintained with continuous tillage practices for the 3 years. However, the result suggests that water in the soil profile at RT could have been increased if reduced tillage practices had been continued. This was previously demonstrated by the previous studies (Linstrom et al., 1984; McIsaac et al., 1990; Radford et al., 1995). Meanwhile, the values of $\theta$ under the different irrigation regimes were greater at 100% $ET_C$

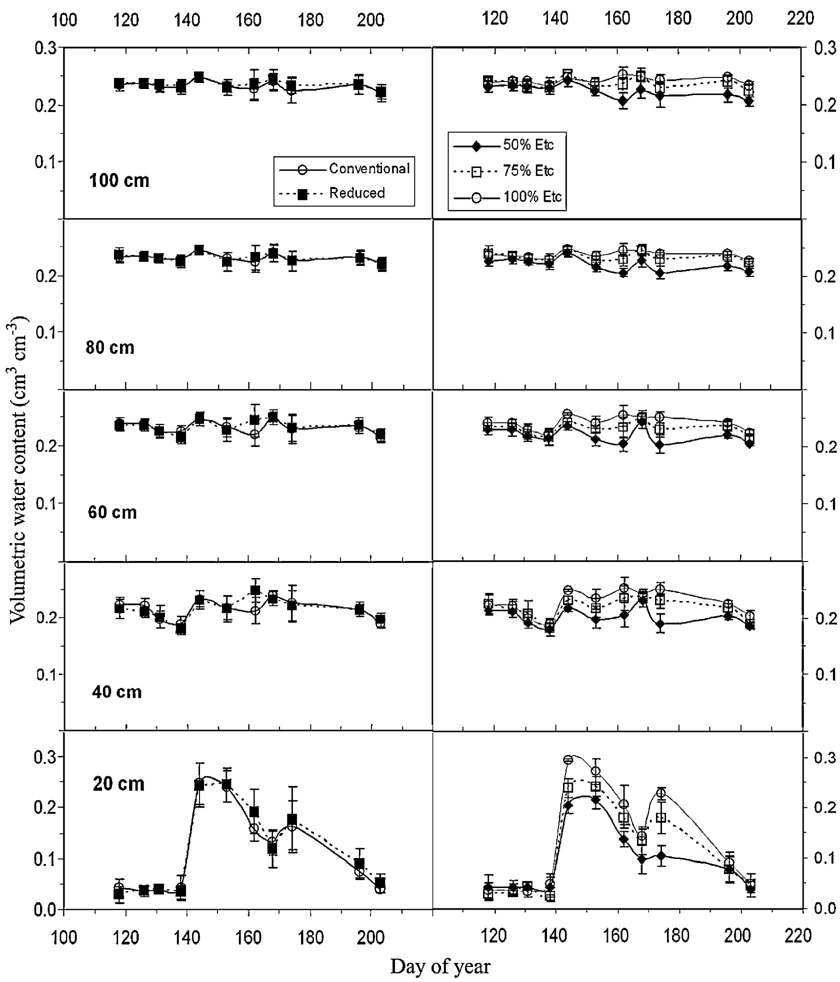


**Fig. 2 – Changes of soil moisture with different tillage practices and irrigation regimes during the growing season at various soil depths in the corn field in 2004. Vertical bars indicate ±1 S.E. (*n* = 27 for tillage treatment and *n* = 18 for irrigation).**

than 75% and 50% $ET_C$ between the growth stages of ~6 leaves and dough. It is assumed that the corn plants under the deficit irrigation regimes experienced water stresses during the periods, resulting in less grain yield. This could be demonstrated with the relationships between the yields and the $\theta$ values (Table 4). Strong correlations were found on DOY 162 and 174, when the $\theta$ values within the irrigation levels were differentiated (refer to Fig. 1). It was advised that summer annual crops such as corn expose yield reductions in response to soil water deficits at any growth phase (Denmead and Shaw, 1960; Howe and Rhoades, 1955). On the other hand, the present result indicates that yield can be adversely affected by stresses in some of the growth stages than others. This was demonstrated by the previous studies (Denmead and Shaw, 1960; Eck, 1984; Musick and Dusek, 1980).

Values of RWC of corn leaves were not significantly different between tillage practices during the season in 2002 (Table 5). Within the irrigation treatments, there were significant differences between 100% and 50% $ET_C$ on DOY 144, 169, and 177. The RWC values at 75% $ET_C$ were greater than those at 50% $ET_C$ on DOY 144 and 169 while they were less than those at 100% $ET_C$ on DOY 169 and 177. There were significant correlations between the RWC and the grain yield on DOY 134, 144, 169, and 177. In addition, seasonal trend of the RWC values generally agreed to that of the $\theta$ values (refer to Fig. 2). We believe that, in most times, RWC can be an effective index of plant water status as it was reported by the previous studies (Barrs, 1968; Smart and Bingham, 1974).

For $T_C$ of the field in 2002, there were significant differences between CT and RT as well as among the different irrigation regimes (Table 6). In addition, significant correlations were found between the $T_C$ and the grain yield. At the same location, Falkenberg et al. (2006) demonstrated that $T_C$ at 50% $ET_C$ regime was statistically greater than those at 75% and 100% $ET_C$ regimes. Meanwhile, since the $T_C$ was monitored with the mixed temperatures of soil and plants, it is considered that the $T_C$ differences between CT and RT are attributable to the differences of some soil physical properties such as water-holding capacity (Opoku and Vyn, 1997; Vyn et al., 1998), structure (Rhoton, 2000), and surface penetrometer resistance (Vyn et al., 1998). Remotely sensed IR imageries show variations of $T_C$ for plant canopies and some of it for the soil surfaces (Fig. 3). There is no doubt that crop $T_C$ is an effective indicator of plant water stress because the temperature of most plant leaves are mediated strongly by soil water availability and its effect on crop evapotranspiration (Jackson,

**Table 4 – Pearson correlation coefficients (*r*) between the grain yields and the seasonal soil moisture at each soil depth.**

| SD (cm) | *r* | | | | | | |
|---|---|---|---|---|---|---|---|
| | DOY138 | DOY153 | DOY162 | DOY168 | DOY174 | DOY196 | DOY203 |
| 20 | ns | 0.45* | 0.56** | ns | 0.50* | ns | ns |
| 40 | ns | 0.48* | 0.63** | ns | 0.48* | ns | 0.37m |
| 60 | ns | 0.40m | 0.61** | ns | 0.53* | ns | 0.47* |
| 80 | ns | ns | 0.62** | ns | 0.46* | ns | 0.39m |
| 100 | ns | 0.45* | 0.56* | ns | 0.50* | ns | ns |

SD, soil depth; DOY, day of year; ns, not significant.
m Significance at the 0.1 probability level.
* Significance at the 0.05 probability level.
** Significance at the 0.01 probability level.

1982; Jackson et al., 1981; Moran et al., 1997). The present result was not different from the previous findings.

Grain yield had comparatively larger correlations with the seasonal average values of $T_C$ and RWC than with that of $\theta$ in each layer (Table 7). Therefore, it is assumed that $T_C$ and RWC can be stronger indicators for plant water stress. Meanwhile, WUE linearly decreased as water input (irrigation + rainfall) increased while grain yield increased with a curvilinear phase (Fig. 4). The greatest WUE (1.6 g $m^{-2}$ $mm^{-1}$) reached at 456 mm of water input and a plateau of grain yield (~8 ton $ha^{-1}$) appears to reach at less than 600 mm of water input. Previously, the relationships between crop yield and irrigation were reported to be linear (Irmak et al., 2000) as well as curvilinear (Cetin and Bilgel, 2002; Yazar et al., 2002b). A corn crop modeling study at the same region (Ko et al., 2007) showed that WUE responded to water input with a parabola-curve pattern, being generally increased until ~600 mm and decreased after that with a linear phase

**Table 5 – Relative water contents of corn leaves under different tillage practices and irrigation regimes, and their correlations with grain yields during the growing season in 2002 at Uvalde, TX.**

| Tillage | Irrigation | % | | | | | |
|---|---|---|---|---|---|---|---|
| | | DOY134 | DOY144 | DOY157 | DOY163 | DOY169 | DOY177 |
| CT | 50% $ET_C$ | 79.2 | 78.0 | 65.8 | 77.2 | 61.5 | 28.2 |
| | 75% $ET_C$ | 83.0 | 86.4 | 63.6 | 76.3 | 69.4 | 53.0 |
| | 100% $ET_C$ | 83.1 | 84.0 | 66.8 | 77.9 | 75.1 | 69.4 |
| RT | 50% $ET_C$ | 76.9 | 81.2 | 66.1 | 66.8 | 68.0 | 28.7 |
| | 75% $ET_C$ | 83.4 | 82.4 | 58.9 | 83.5 | 72.2 | 18.2 |
| | 100% $ET_C$ | 81.3 | 86.5 | 68.8 | 74.7 | 72.1 | 81.7 |
| Means within tillage | CT | 81.8 a | 82.8 a | 65.4 a | 76.8 a | 68.6 a | 50.2 a |
| | RT | 80.5 a | 83.4 a | 64.6 a | 75.0 a | 71.7 a | 42.8 a |
| Means within irrigation | 50% $ET_C$ | 78.0 a | 79.6 b | 66.0 a | 72.0 a | 64.7 b | 28.4 b |
| | 75% $ET_C$ | 83.2 a | 84.4 a | 61.2 a | 75.8 a | 70.8 ab | 35.6 b |
| | 100% $ET_C$ | 82.2 a | 85.2 a | 67.9 a | 79.3 a | 73.6 a | 75.5 a |

| AVOVA | $P > F$ | | | | | |
|---|---|---|---|---|---|---|
| | DOY134 | DOY144 | DOY157 | DOY163 | DOY169 | DOY177 |
| Tillage (*T*) | ns | ns | ns | ns | ns | ns |
| Irrigation (*I*) | ns | * | ns | ns | * | ** |
| $T \times I$ | ns | ns | ns | ns | ns | * |

| Correlation with yield | $r^a$ | | | | | |
|---|---|---|---|---|---|---|
| | DOY134 | DOY144 | DOY157 | DOY163 | DOY169 | DOY177 |
| | 0.54* | 0.56* | 0.12 | 0.35m | 0.44* | 0.50* |

CT, conventional tillage; RT, reduced tillage; $ET_C$, crop evapotranspiration; DOY, day of year; ns, not significant. Means followed by the same letter within each column are not significantly different (LSD test at the 0.05 probability level).
a *r* is Pearson correlation coefficient.
m Significance at the 0.1 probability level.
* Significance at the 0.05 probability level.
** Significance at the 0.01 probability level.

**Table 6 – Canopy temperatures of the corn field under different tillage practices and irrigation regimes, and their correlations with the grain yields during the growing season in 2002 at Uvalde, TX.**

| Tillage | Irrigation | °C | | | | |
|---|---|---|---|---|---|---|
| | | DOY157 | DOY161 | DOY164 | DOY171 | DOY176 |
| CT | 50% $ET_C$ | 34.6 | 31.4 | 31.2 | 34.5 | 32.3 |
| | 75% $ET_C$ | 30.3 | 30.1 | 30.7 | 31.6 | 31.0 |
| | 100% $ET_C$ | 29.5 | 29.1 | 30.5 | 30.4 | 29.5 |
| RT | 50% $ET_C$ | 30.4 | 31.0 | 32.1 | 31.6 | 32.8 |
| | 75% $ET_C$ | 31.3 | 29.9 | 30.4 | 30.9 | 31.7 |
| | 100% $ET_C$ | 28.4 | 29.1 | 30.3 | 29.9 | 29.8 |
| Means within tillage | CT | 31.5 a | 30.2 a | 30.9 a | 32.2 a | 30.9 b |
| | RT | 30.0 b | 30.0 b | 30.8 a | 30.8 b | 31.4 a |
| Means within irrigation | 50% $ET_C$ | 32.5 a | 31.2 a | 31.6 a | 33.0 a | 32.6 a |
| | 75% $ET_C$ | 30.8 b | 30.0 b | 30.6 b | 31.2 b | 31.4 b |
| | 100% $ET_C$ | 28.9 c | 29.1 c | 30.4 b | 30.2 c | 29.6 c |
| ANOVA | | $P > F$ | | | | |
| | | DOY157 | DOY161 | DOY164 | DOY171 | DOY176 |
| Tillage ($T$) | | *** | ** | ns | *** | *** |
| Irrigation ($I$) | | *** | *** | *** | *** | *** |
| $T \times I$ | | *** | ns | *** | *** | ns |
| Correlation with yield | | $r$[a] | | | | |
| | | DOY157 | DOY161 | DOY164 | DOY171 | DOY176 |
| | | $-0.61^{**}$ | $-0.69^{***}$ | $-0.56^{**}$ | $-0.65^{**}$ | $-0.52^{*}$ |

CT, conventional tillage; RT, reduced tillage; $ET_C$, crop evapotranspiration; DOY, day of year. Means followed by the same letter within each column are not significantly different (LSD test at the 0.05 probability level).

[a] $r$ is Pearson correlation coefficient.

* Significance at 0.05.

** Significance at 0.01.

*** Significance at 0.001.

(Fig. 5A). Meanwhile, the relationships between crop yield and $ET_C$ were reported to be linear (Jalota et al., 2006; Oktem et al., 2003; Payero et al., 2006; Yazar et al., 2002a). At the same region to the present study, Ko et al. (2007) showed that grain yield responded to water input with a threshold-like curve pattern, being linearly increased until 700 mm and reached a plateau after that (Fig. 5B). As the simulation study was performed representing the region of the environments (e.g., reasonably similar soil and weather conditions), it is believed that the present study results can be comparable to the simulation study results. The results demonstrate that WUE reached a decreasing phase and grain yield reached a plateau at less water input than that of the simulation results. Therefore, it appears that $ET_C$-based irrigation is one

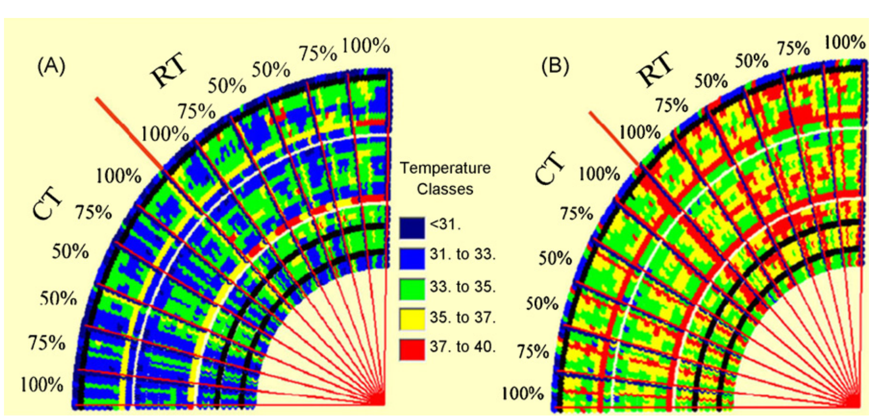


**Fig. 3 – Infrared camera photographs of the corn field under different tillage practices and irrigation regimes on day of year (DOY) 141 (A) and 145 (B) in 2002. Temperature unit is Celsius; CT and RT stand for conventional and reduced tillage; 100%, 75%, and 50% represent irrigations with 100%, 75%, and 50% crop evapotranspiration.**

**Table 7 – Pearson correlation coefficients (*r*) between the grain yields with canopy temperature ($T_C$), relative water content (RWC), and soil moisture ($\theta$) in each soil depth.**

| Variable | *r* |
|---|---|
| $T_C$ | −0.69** |
| RWC | 0.66** |
| $\theta$ in 20 cm | 0.37 |
| $\theta$ in 40 cm | 0.40* |
| $\theta$ in 60 cm | 0.48* |
| $\theta$ in 80 cm | 0.42* |
| $\theta$ in 100 cm | 0.49* |

* Significance at 0.05.
** Significance at 0.01.

of the efficient water delivery schemes, resulting in greater WUE and grain yield with less water input.

As mentioned in Section 1, irrigation application at critical growth stages is one of the important factors to improve the efficiency of crop water use and to achieve optimal crop production. Denmead and Shaw (1960) in Iowa reported that stress at silking reduced yield by 50%, whereas stress during the vegetative stage and after silking reduced yield by 25% and 21%, respectively. Musick and Dusek (1980) in the Texas

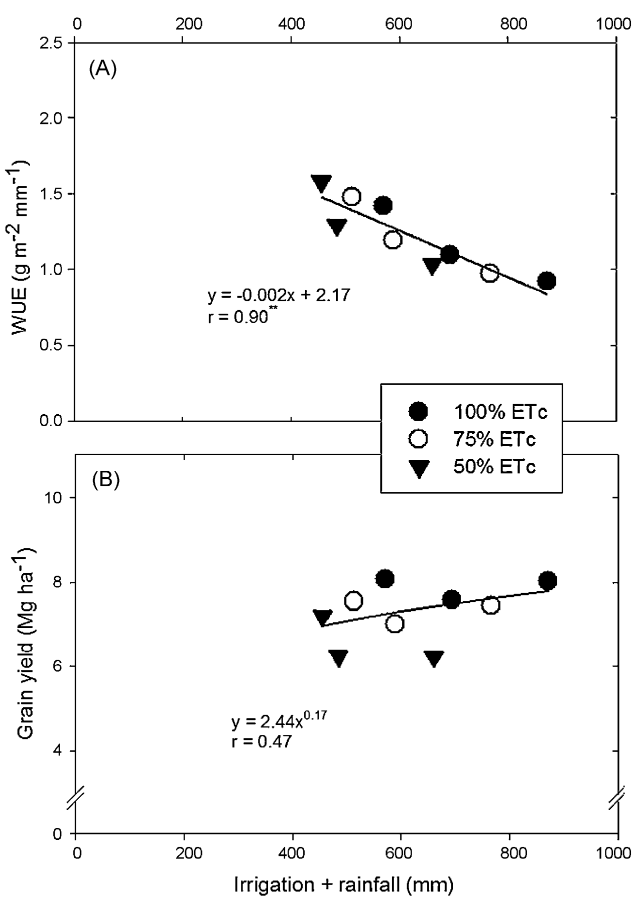


**Fig. 4 – Water use efficiency (WUE) vs irrigation + rainfall (A) and Grain yield vs irrigation + rainfall (B), using data obtained at different irrigation regimes in 2002, 2003, and 2004. ** represents significance at the 0.01 probability level.**

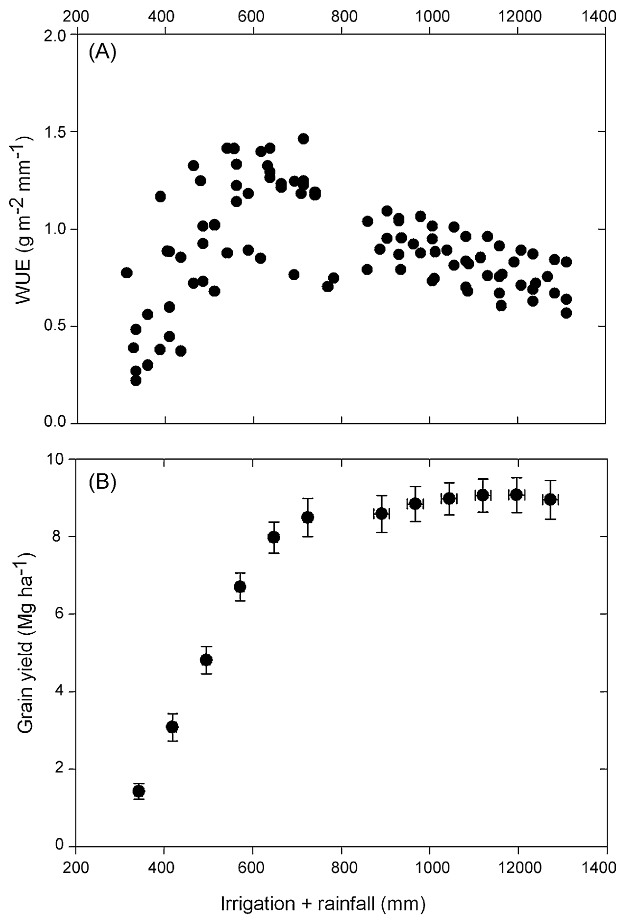


**Fig. 5 – Water use efficiency (WUE) vs irrigation + rainfall (B) and grain yield vs irrigation + rainfall (B). These were determined using EPIC crop simulation with various irrigation scenarios (reproduced from Ko et al., 2007).**

Panhandle reported that stress during tasseling and silking was the most harmful and stress during grain filling was more harmful than stress during vegetative growth. The irrigation management applied for this study was practiced based on actual crop water requirement. Continuous efforts to improve irrigation efficiency will be beneficial for researchers and producers who seek for irrigation decision support tools.

## 4. Summary and conclusions

Improving irrigation water management for crop production is becoming important in South Texas as the water supplies shrink and competition with urban centers in the region grows. In this study, yield responses under full and deficit irrigations based on crop $ET_C$ and factors affecting yield reduction were described: the grain yields were increased as irrigation increased; there were significant differences in $\theta$ of the soil and RWC of corn leaves between 100% and 50% $ET_C$; values of $T_C$ were significantly different among the different irrigation regimes. While $\theta$ is considered to be one of the causes of corn grain yield reduction, the result showed that RWC and $T_C$ can be used as strong indicators for plant water stress. The greatest water use efficiency (WUE, 1.6 g $m^{-2}$ $mm^{-1}$) reached at 456 mm of water input while grain yield appeared to reach a plateau (~8 ton $ha^{-1}$) at less than 600 mm. It was demonstrated that WUE reached a decreasing phase and grain yield reached a plateau at less water input than that of the simulation results performed in the same region by Ko et al. (2007). Therefore, it is assumed that $ET_C$-based irrigation is one of the efficient water delivery schemes, resulting in greater WUE and grain yield with less water input. While irrigation application at critical growth stages is one of the important factors to improve the efficiency of crop water use and to achieve optimal crop production, the irrigation management applied in this study was practiced based on actual crop water requirement.

## Acknowledgements

This study is partially funded by Texas Water Development Board (TWDB: Project No. 0603580596) and Rio Grande Basin Initiative (RGBI: Grant No. 2005-34461-15661). The authors would like to express his appreciation to Texas Water Resources Institute (TWRI) for administrative project assistance. We also thank Dr. Clothier and the anonymous reviewers for their valuable comments.

## REFERENCES

Allen, R., Pereira, L., Raes, D., Smith, M., 1998. Crop evapotranspiration. FAO Irrigation and Drainage Paper 56, Food and Agriculture Organization of the United Nations, Rome, Italy.

Barrs, H.D., 1968. Determination of water deficits in plant tissues. In: Kozlowski, T.T. (Ed.), Water Deficits and Plant Growth, vol. 1. Academic Press, New York, pp. 235–368.

Barrett, M.E., 1999. Complying with the Edwards Aquifer rules: technical guidance on best management practices/prepared for Field Operation Division, Austin, TX. Texas Natural Resource Conservation Commission 1: RG–348 (variously paged).

Cetin, O., Bilgel, L., 2002. Effects of different irrigation methods on shedding and yield of cotton. Agric. Water Manage. 54, 1–15.

Clawson, K.L., Blad, B.L., 1982. Infrared thermometry for scheduling irrigation of corn. Agron. J. 74, 311–316.

Denmead, O.T., Shaw, R.H., 1960. The effects of soil moisture stress at different stages of corn growth on the development and yield of corn. Agron. J. 52, 272–274.

Eck, H.V., 1984. Irrigated corn yield responses to nitrogen and water. Agron. J. 76, 412–428.

Falkenberg, N.R., Piccinni, G., Cothren, J.T., Leskovar, D.I., 2006. Remote sensing of biotic and abiotic stress for irrigation management of cotton. Agric. Water Manage. 87, 23–31.

Hergert, G.W., Klocke, N.L., Petersen, J.L., Norquist, P.T., Clarke, R.T., Wicks, G.A., 1993. Cropping systems for stretching limited irrigation supplies. J. Prod. Agric. 6, 520–529.

Howe, O.W., Rhoades, H.F., 1955. Irrigation practice for corn production in relation to stage of plant development. Soil Sci. Soc. Am. Proc. 19, 94–98.

Howell, T.A., Cuenca, R.H., Soloman, K.H., 1990. Crop yield response. In: Hoffman, G.J., et al. (Eds.), Management of Farm Irrigation Systems. ASAE Monogr. ASAE, St. Joseph, MI, pp. 93–122.

Howell, T.A., Tolk, J.A., Schneider, A.D., Evett, S.R., 1998. Evapotranspiration, yield, and water use efficiency of corn hybrids differing in maturity. Agron. J. 90, 3–9.

Howell, T.A., Yazar, A., Schneider, A.D., Dusek, D.A., Copeland, K.S., 1995. Yield and water use efficiency of corn in response to LEPA irrigation. Trans. ASAE 38, 1737–1747.

Irmak, S., Haman, D.Z., Bastug, R., 2000. Determination of crop water stress index for irrigation timing and yield estimation of corn. Agron. J. 92, 1221–1227.

Jackson, R.D., 1982. In: Hilled, D.I. (Ed.), Canopy Temperature and Crop Water Stress, Advances in Irrigation, vol. 1. Academic Press, New York, NY, pp. 43–85.

Jackson, R.D., Idso, S.B., Reginato, R.J., Pinter Jr., P.J., 1981. Canopy temperature as a crop water stress indicator. Water Resour. Res. 17, 1133–1138.

Jalota, S.K., Sood, A., Chahal, G.B.S., Choudhury, B.U., 2006. Crop water productivity of cotton (*Gossypium hirsutum* L.)-wheat (*Triticum aestivum* L.) system as influenced by deficit irrigation, soil texture and precipitation. Agric. Water Manage. 84, 137–146.

Ko, J., Piccinni, G., Steglich, E., Gerik, T.J., Marek, T., Howell, T., Kemanian, A., 2007. Using EPIC simulation model to manage irrigated crops. In: ASA-CSSA-SSA 2007 International Annual Meetings. New Orleans, LA, November 4–8 (CD-ROM).

Kozlowski, T.T. (Ed.), 1972. Water Deficits and Plant Growth. Academic Press, New York.

Kramer, P.J., Boyer, J.S., 1995. Water Relations of Plants and Soils. Academic Press, San Diego, CA.

Lindstrom, M.J., Forcella, F., 1990. Tillage and residue management effects on crop production in the northwestern Corn Belt. In: Challenges in Dryland Agriculture: A Global Perspective. Proceedings of the International Conference on Dryland Farming, Amarillo and Bushland, TX, 15–19 August 1988. Texas Agric. Exp. Stn., Bushland, pp. 565–567.

Linstrom, M.J., Voorhees, W.B., Onstad, C.A., 1984. Tillage and residue cover effects on infiltration in northwestern Corn Belt soils. J. Soil Water Conserv. 39, 64–69.

McIsaac, G.F., Mitchell, J.K., Hirschil, M.C., 1990. Contour and conservation tillage for corn and soybean in the Tama silt loam soil: hydraulics and sediment concentration. Trans. ASAE 33, 1541–1550.

Michels Jr., G.J., Piccinni, G., Rush, C.M., Fritts, D.A., 1999. Using infrared transducers to sense greenbug (*Homoptera: Aphididae*) infestations in winter wheat. Southwest. Entomol. 24, 269–279.

Mock, J.J., Erbach, D.C., 1997. Influence of conservation-tillage environments on growth and productivity of corn. Agron. J. 69, 337–340.

Moran, M.S., Inoune, Y., Barnes, E.M., 1997. Opportunities and limitations for image-based remote sensing in precision crop management. Remote Sens. Environ. 61, 319–346.

Musick, J.T., Dusek, D.A., 1980. Irrigated corn yield response to water. Trans. ASAE 23, 92–98 103.

Oktem, A., Simsek, M., Oktem, A.G., 2003. Deficit irrigation effects on sweet corn (*Zea mays saccharata Sturt*) with drip irrigation system in a semi-arid region. I. Water-yield relationship. Agric. Water Manage. 61, 63–74.

Opoku, G., Vyn, T.J., 1997. Wheat residue management option for no-till corn. Can. J. Plant Sci. 78, 207–213.

Payero, J.O., Melvin, S.R., Irmak, S., Tarkalson, D., 2006. Yield response of corn to deficit irrigation in a semiarid climate. Agric. Water Manage. 84, 101–112.

Radford, B.J., Dry, A.J., Robertson, L.N., Thomas, B.A., 1995. Conservation tillage increases soil water storage, soil

animal populations, grain yield, and response to fertilizer in the semi-arid subtropics. Aust. J. Exp. Agric. 35, 223–232.
Rhoton, F.E., 2000. Influence of time on soil response to no-till practices. Soil Sci. Soc. Am. J. 64, 700–709.
Salisbury, F.B., Ross, C.W., 1992. Plant Physiology, 4th ed. Wadsworth Publ. Co., Belmont, CA.
Smart, R.E., Bingham, G.E., 1974. Rapid estimates of relative water content. Plant Physiol. 53, 258–260.
Smart, J.R., Bradford, J.R., 1999. Conservation tillage corn production for a semiarid, subtropical environment. Agron. J. 91, 116–121.
Stegman, E.C., 1982. Corn grain yield as influenced by timing of evapotranspiration deficits. Irrig. Sci. 3, 75–87.
Stewart, D.A., Nielsen, D.R. (Eds.), 1990. Irrigation of Agricultural Crops. Agron. Monogr. ASA, Madison, WI, p. 30.
Taylor, H.M., Jordan, W.R., Sinclair, T.R., 1983. Limitation to Efficient Water Use in Crop Production. ASA-CSSA-SSSA, Inc., Madison, WI.
Tolk, A.J., Howell, T.A., Evett, S.R., 1998. Evapotranspiration and yield of corn grown on three High Plains soils. Agron. J. 90, 447–454.
Vyn, T.J., Opoku, G., Swanton, C.J., 1998. Residue management and minimum tillage systems for soybean following wheat. Agron. J. 90, 131–138..
Weatherley, P.E., 1950. Studies in the water relations of the cotton plant. I. The filed measurement of water deficits in leaves. New Phytol. 49, 81–97.
Weatherley, P.E., 1951. Studies on the water relations of the cotton plant. II. Diurnal and seasonal variations in relative turgidity and environmental factors. New Phytol. 50, 36–51.
Yazar, A., Sezen, S.M., Gencel, B., 2002a. Drip irrigation of corn in the Southeast Anatolia Project (GAP) area in Turkey. Irrig. Drain. 51, 293–300.
Yazar, A., Sezen, S.M., Sesveren, S., 2002b. LEPA and trickle irrigation of cotton in the Southeast Anatolia Project (GAP) area in Turkey. Agric. Water Manage. 54, 189–203.